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Procedia Engineering 81 (2014) 1535 – 1540

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Deformation behavior of high-manganese TWIP steels produced by twin-roll strip casting

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Abstract

Twin-roll strip casting represents a promising alternative for the production of high manganese steels. The present work demonstrates the opportunities for the production and further processing of a Fe-17Mn-0.6C-1.5Al TWIP steel. The mechanical properties are increased along the process chain and the cold strip exhibits a true stress of σ = 1500 MPa at a logarithmic strain of ε = 0.5. Combined EPMA and EBSD measurements allow for analyzing the influence of the inhomogeneous as-cast structure with pronounced microsegregations on twinning behavior. It was shown that twinning starts in the areas with a lower element concentration and thus with a lower local stacking fault energy. In addition, the fine as-cast structure with segregations only on the micron-scale has no negative influence on the resulting mechanical properties in the recrystallized cold strip.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Twin-roll strip casting; High manganese steel; Twinning; Microstructure; Mechanical Properties

1. Introduction

Near-net-shape strip casting represents a promising opportunity for producing high-manganese TWIP steels. This applies in particular to steel grades with aluminum contents of more than 1.5 wt%, which cause serious

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.10.186

problems in conventional casting processes using casting powders [1]. The cast strip is characterized by the typical as-cast microstructure containing pronounced microsegregations and an inhomogeneous grain distribution [2]. Despite the detrimental, inhomogeneous microstructure of the high-manganese strip produced via strip casting, the good mechanical properties have already been shown in tensile tests and stack compression tests [3]. Further processing of the as-cast strip by cold rolling and short time annealing enables the production of recrystallized cold strip with a homogeneous grain structure and a grain size of 10 µm in a considerably shortened process chain. In addition, increased mechanical properties are achieved in the cold strip, comparable to material of a conventional production line [4].

Both the as-cast strip and the cold strip are characterized by the as-cast structure and exhibit locally pronounced fluctuations in element concentration of the main alloying elements. The work of Saeed-Akbari showed that the chemical composition has a major influence on the stacking fault energy (SFE) and thus on the occurring forming mechanisms [5]. Accordingly, an influence of the local element concentration in the strip cast material on the formation of deformation twins and on the resulting mechanical properties is expected.

The goal of this work was to investigate to what extent the mechanical properties can be affected by the single process steps along the short process chain and to determine the influence of the inhomogeneous dendritic microstructure on the deformation behavior. Accordingly, a strip cast Fe-17Mn-0.6C-1.5Al TWIP steel is further processed by cold rolling and subsequent annealing to achieve a fully recrystallized grain distribution. To characterize the evolution of the mechanical properties, tensile tests in all states of the material are carried out. In addition, the impact of the local chemical composition on the formation of twins can be assessed by means of electron probe microanalysis (EPMA) and electron backscatter diffraction (EBSD). The combined analysis helps to understand whether the formation of twins is preferred in areas with low or high SFE. An additional homogenization step prior to cold rolling allows for comparing the influence of different local element concentrations on the forming behavior.

2. Experimental procedure

2.1. Material

For the work performed, a high-manganese steel Fe-17Mn-0.6C-1.5Al was selected. In accordance to the calculated SFE of 27 mJ/m², the forming behavior is characterized by the formation of deformation twins [5]. The investigated material was produced at the lab-scale twin-roll caster at the Institute of Metal Forming (IBF) of RWTH Aachen University. The design of the strip caster and the casting sequence are described in detail in [2].

In the present work, the melt was poured in the roll gap with a superheating of 50 K above the liquidus temperature and solidified in less than 0.4 s with cooling rates up to 1000 K/s. A roll separating force of 25 kN was used at a casting speed of 0.5 m/s. The solidified strip left the roll gap with a measured surface temperature of approximately 1350 °C and had a thickness of 2.4 mm and a width of 150 mm. In the subsequent inline hot rolling step at approximately 1100 °C, the strip thickness was reduced to 2.0 mm at a rolling force of 600 kN, before the material was coiled. The chemical composition of the hot rolled strip is listed in Table 1.

Table 1. Chemical composition of the investigated Fe-17Mn-0.6C-1.5Al in the different states of material measured by OES.

Fe-17Mn-0.6C-1.5Al	Fe in wt%	Mn in wt%	C in wt%	Al in wt%
Cast and inline hot rolled strip	Bal	17.45	0.583	1.488
Recrystallized cold strip	Bal	17.61	0.576	1.500
Homogenized cold strip	Bal	17.51	0.572	1.491

2.2. Further processing

The 2 mm hot rolled strip was cold rolled at the IBF workshop with a lab scale rolling mill with a four-high configuration. A thickness reduction of 50 % ensured that the introduced forming energy was sufficient for the recrystallization of the 1 mm cold rolled strip. To achieve the desired thickness, 5 rolling steps at the maximum rolling force of 1.4 MN were performed. The material was then subjected to a 15 min annealing procedure at 900 °C in an argon atmosphere to achieve a fully recrystallized microstructure. The entire process line is depicted schematically in Fig. 1. Besides, homogenized cold strip was produced by adding an additional annealing prior to the cold rolling at a temperature of 1150 °C for 60 min, to dissolve the microsegregations. This homogenization annealing took also place in an argon atmosphere. The different states of the material and the obtained thicknesses and grain sizes are shown in Table 2.

Table 2. Produced material for the material characterization.

Fe-17Mn-0.6C-1.5Al	Thickness in mm	Grain size in µm	Microstructure
As-cast strip	2.4	> 150	Dendritic
Inline hot rolled strip	2.0	> 150	Dendritic
Recrystallized cold strip	1.0	10	Recrystallized
Homogenized cold strip	1.0	10	Recrystallized

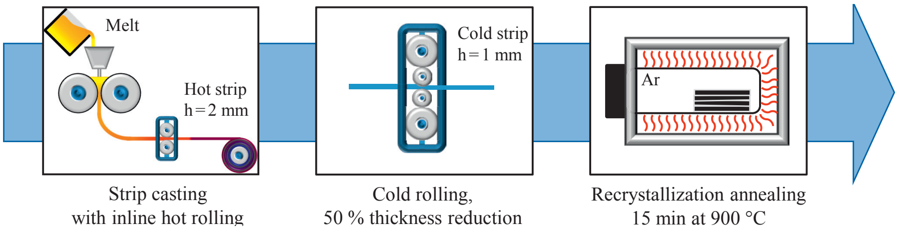

Fig. 1. Process line for the production of high-manganese, cold rolled strip via twin-roll strip casting at IBF.

2.3. Material characterization and microstructural analysis

Uniaxial tensile tests were performed at room temperature for all produced states of material using a Zwick 4204 universal testing machine. The tested specimens were machined along the rolling direction and an A30 sample geometry with a parallel length of 30 mm was applied. A constant traverse speed of 4.5 mm/s was used to achieve quasi-static deformation at a strain rate of 0.0025 s^{-1}. For analyzing the twinning behavior, tensile tests were performed with a logarithmic strain of $\varepsilon = 0.10$ and 0.20.

For the analysis of the microstructure, specimens of the as-cast, recrystallized and homogenized strip at $\varepsilon = 0.20$ were investigated. The samples were polished to 0.05 µm colloidal silica. No repolishing was performed in between the EPMA and EBSD measurements.

The local element distribution was characterized by using a field emission electron probe microanalyzer at the Central Facility for Electron Microscopy (GFE). An electron beam energy of 15 keV and an electron beam current of 100 nA was used. Element mappings of an area 200 x 200 µm² and line scans over a length of 100 µm with a step size of 100 nm were measured to obtain the mass concentrations of the elements manganese, carbon and aluminum. Details about the measurement and quantification can be found in [6]. All measurements were performed in a distance of about 100 µm from the strip surface. The measured results were then matched with the results of optical emission spectrometry (OES), see Table 1.

A JEOL JSM-7000 field emission scanning electron microprobe used for the EBSD measurements with an EDAX-TSL Hikari XP detector. Measurements were made at an accelerating voltage of 20 keV with a probe current of approximately 30 nA and a step size of 200 nm. The criterion for the definition of twin boundaries was 60° misorientation about the <111> axis, with an angular tolerance of 5° within the austenitic (fcc) matrix. The same area of 200 x 200 µm² was scanned in order to directly compare the EPMA and EBSD results.

3. Results

The applied process line enables the production of as-cast, hot rolled and recrystallized cold strip with a high surface quality without any microcracks. The as-cast strip already exhibits good mechanical properties with a yield stress of $R_{p0.2}$ = 314 MPa, an ultimate tensile strength of R_m = 724 MPa at a uniform elongation of A_g = 54.0 %. Due to the inline hot forming, the stress level is increased in the hot strip regarding the yield stress and ultimate tensile strength. The uniform elongation is increased to A_g = 59.0 %. Both cold strips show similar yield stresses compared to the as-cast material of $R_{p0.2}$ = 314 MPa. However, the best combination of ultimate tensile strength R_m = 875 MPa and uniform elongation of approximately A_g = 65.0 % is achieved after cold rolling and annealing. In addition, the homogenization step led to a slightly increased formability. All results of the uniaxial tensile tests are presented in Table 3.

Table 3. Mechanical properties of the investigated as-cast, inline hot rolled, recrystallized and homogenized strip.

Fe-17Mn-0.6C-1.5Al	$R_{p0,2}$ in MPa	R_m in MPa	A_g in %
As-cast strip	314	724	54.0
Inline hot rolled strip	443	814	59.0
Recrystallized cold strip	328	875	64.7
Homogenized cold strip	332	874	68.5

A dendritic microstructure with pronounced microsegregations is characteristic for the as-cast material, as shown in the element mapping of the manganese content at a log. strain of ε = 0.20 in Fig. 2 a). The dendrites with a secondary dendrite arm spacing (SDAS) of approximately 5 µm of two crystals with different orientation are clearly visible. The resulting deviations in element concentration are $\Delta c(Mn)$=4 wt%, $\Delta c(C)$=0.12 wt% and $\Delta c(Al)$ =0.23 wt%. Mn and C segregate interdendritically, whereas Al has the highest concentration inside the dendrites.

Regarding the EBSD-IQ map of the as-cast material at a log. strain of ε = 0.20 (Fig. 2 b)), the large grain size is obvious and deformation twins were detected in the marginal grains. At a strain of ε = 0.10 no twin bundles were detected. The growth of the twins is only limited by the grain boundaries, not by the dendritic structure.

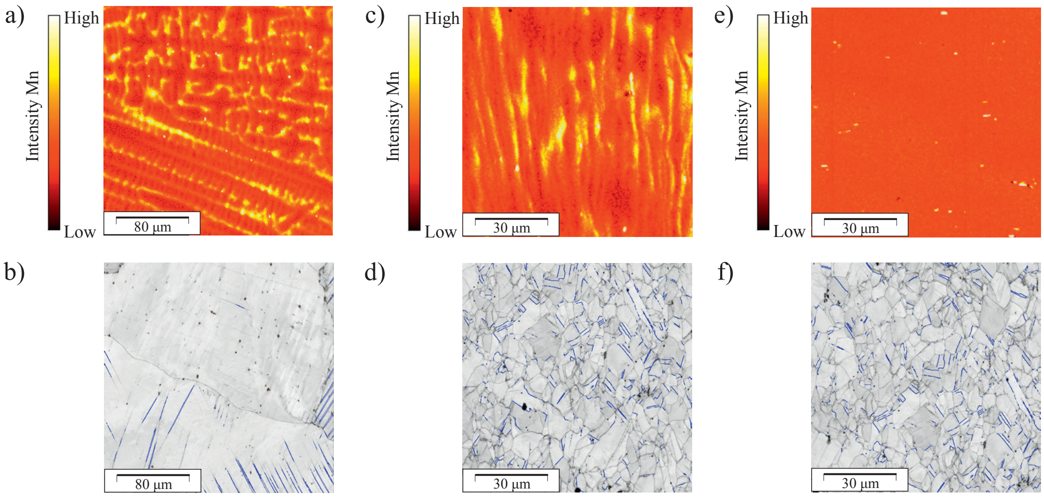

Fig. 2. Element mapping of manganese content and EBSD-IQ map of (a), (b) as-cast material, (c), (d) recrystallized cold strip and (e), (f) homogenized strip at a logarithmic strain of ε = 0.20. The detected grain boundaries and twins appear dark in the IQ map.

Considerable segregation areas can be seen in the element mapping of the recrystallized cold strip in Fig. 2 c). The local concentration gradients were hardly dissolved and the deviations of the manganese content are $\Delta c(Mn)$ = 2.1 wt%. However, the wavelength of the segregations has been halved by the thickness reduction in cold rolling. A homogeneous grain distribution with an average grain size of 10 µm was detected by EBSD. Both annealing twins and deformation twins appeared in the recrystallized strip.

The homogenized strip shows a completely homogeneous manganese concentration with Δc(Mn) = 0.2 wt%, as seen in Fig. 2 e). However, the carbon distribution was hardly affected by the additional heat treatment. Grain distribution with a grain size of 10 µm and twinning are similar to the recrystallized strip (cf. Fig. 2f)).

4. Discussion

4.1. Influence of different process steps on mechanical properties

A noticeable improvement of the mechanical properties along the process line starting from as-cast strip over hot strip up to cold strip was observed and is depicted in Fig. 3 a). Despite the existing segregations, the cold strip shows remarkable properties with a flow stress of 1500 MPa at a logarithmic strain of 0.5. Regarding the work hardening behavior, all investigated material states show the typical s-shape of TWIP steel. The cold strip exhibits an advantageous, steady drop of the work hardening rate. Measured differences of the mechanical properties and the work hardening behavior are due to the different grain sizes, accordingly to the dynamic Hall Petch effect [7]. It was shown that the additional homogenization annealing had only a small impact on the flow behavior.

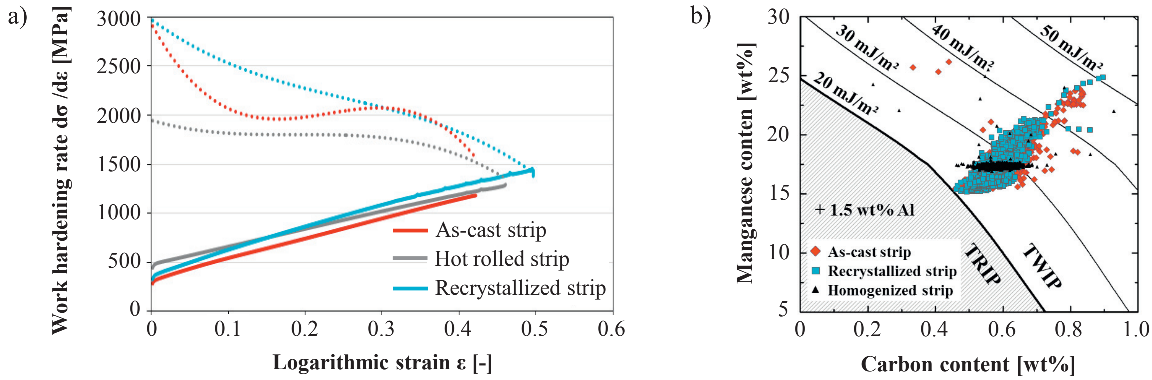

Fig. 3. (a) Flow curves and work hardening behavior of the as-cast, hot rolled and cold rolled strip and (b) mechanism map, containing 1.5 wt% Al with measured element distribution of manganese and carbon.

4.2. Local element distribution and twinning behavior

Fig. 3 b) shows the measured local element distribution and the calculated stacking fault energy in one diagram. The result reveals a large range in the mechanism map for the as-cast (red rhombus) and cold strip (blue square). No significant homogenization of the recrystallized material took place and pronounced fluctuations in Mn and C are evident. According to the mechanism maps of Saeed-Akbari [5], the inhomogeneous element distribution results in a wide range of SFE of 20 to 40 mJ/m², but all values are in the TWIP area. It has to be assumed that the different values of stacking fault energy affect the twinning behavior and the mechanical properties. Furthermore, the positive influence of the homogenization annealing on the local manganese concentration (black triangle) which is reduced to a minimum can be seen in Fig. 3 b). However, the concentration gradient of C remains almost constant and the calculated SFE varies in the range of 25-30 mJ/m².

By combining EPMA and EBSD results, it is possible to consider the twinning behavior in accordance to the local element distribution. The analysis of the as-cast strip shows that the grain boundaries grow along the dendritic crystals. Concerning the twinning behavior, the deformation twins form at the grain boundaries of such grains with a preferred <111> orientation and grow without regard to the dendritic structure throughout the entire grains. An influence of the segregation areas on the formation or growth of the twins is not observed.

Regarding the results of the performed investigations in terms of the recrystallized cold strip in Fig. 4 b), a connection between the local element distribution and the formation of deformation twins is noticeable. Whereas in the bright areas, representing areas with a high SFE according to the enriched element concentration, no twin bundles are detected, several grains in the dark areas show a remarkable number of deformation twins (arrows in Fig. 4 b)). It has to be assumed that twinning starts in the low SFE areas, whereas the nucleation is inhibited in the highly alloyed areas with a considerable higher SFE. To confirm this assumption, further investigation of the nucleation has to be taken into consideration by means of TEM. The growth of the twins during forming is then dominated by the grain orientation and starts in grains with a preferred <111> orientation.

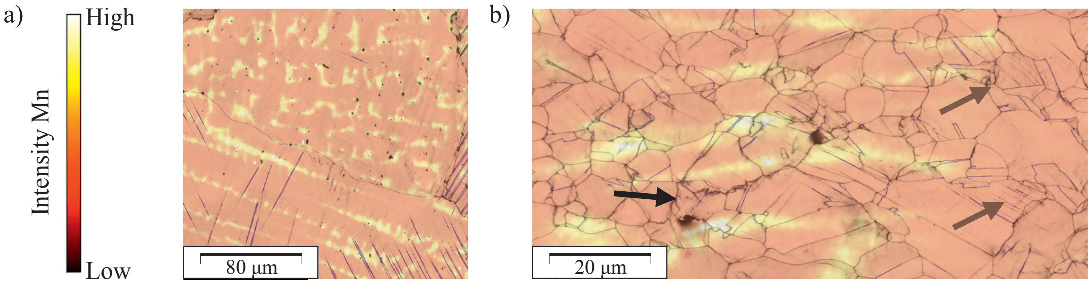

Fig. 4. Comparison of Mn distribution measured by EPMA and EBSD-IQ map of (a) as-cast material and (b) recrystallized material with detected twin bundles in the marked areas of low SFE.

Despite the influence of the segregations on twinning behavior, the mechanical properties are hardly affected by the inhomogeneous element distribution. This is due to the fact that the segregation areas show a period of less than 3 µm and are distributed stochastically. Thus, a homogeneous forming behavior is expected.

5. Conclusion

High-manganese TWIP steel Fe-17Mn-0.6C-1.5Al was produced via twin-roll strip casting and further processed to recrystallized cold strip. Besides the mechanical properties, the twinning behavior depending on the local element distribution was investigated by means of EPMA and EBSD. The following conclusions were drawn:

(1) The short process line enables an economical production of high-manganese steels and the mechanical properties are increased along the entire process line. Despite the pronounced inhomogeneities of the microstructure, the cold strip shows an excellent forming behavior.
(2) An additional annealing step is sufficient for the homogenization of the element distribution, but no large influence on the material properties is detected.
(3) The local element concentration results in a wide range of the calculated SFE. Accordingly, it was shown that deformation twins in the cold rolled strip only exist in the low-alloyed areas with low SFE values. It has to be assumed that due to the fine as-cast structure, only segregation areas on the micron-scale occur which are distributed stochastically and do not affect the mechanical properties in a negative manner.

Acknowledgements

The authors gratefully acknowledge the financial support of Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center (SFB) 761 “Stahl – *ab initio*” and ThyssenKrupp Steel Europe AG.

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